Overlaying Images: Spatial Transformations of Complex Visualizations

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Introduction

There are many tools to help scientists visualize data, ranging from Excel to sophisticated graphing packages that allow a scientist to look at multivariate and multidimensional data in a variety of ways. These visualization tools are considered essential, given the amount and complexity of the data that many scientists work with. Previous researchers, however, have emphasized the importance of mental imagery in scientific discovery (Kaplan & Simon, 1990; Shepard, 1988; Thomas, 1999). What is the relationship between scientific visualization and mental imagery?

There are, of course, several possibilities. First, it could be that because scientists have access to such powerful visualization tools, mental imagery is used only when scientists do not have access to the explicit scientific visualizations. Another possibility is that scientists build up some sort of spatial representation of the data (similar, perhaps, to the qualitative mental model discussed in Trafton et al., 2000), and then explore that spatial representation with the visualization tools. If this latter possibility is true, how do scientists make the connection between images on the screen and images in the head?

We are primarily interested in how working scientists use mental imagery and the relationship of mental imagery to computer-generated scientific visualizations. Thus, we will use the *in vivo* approach pioneered by Dunbar (1995, 1996).

In order to explore these issues, we have developed a framework for coding and working with spatial imagery called *Spatial Transformations*. Spatial Transformations are cognitive operations that a scientist performs on a visualization. Sample spatial transformations are mental rotation (e.g., Shepard & Metzler, 1971), creating a mental image, modifying that mental image by adding or deleting features to or from it, time series progression prediction, mentally moving an object, mentally transforming a 2D view into a 3D view (or vice versa), comparisons between different views (Kosslyn, Sukel, & Bly, 1999), and anything else a scientist mentally does to a visualization in order to understand it or facilitate problem solving. Also note that a spatial transformation can be done on either an internal (i.e., mental) image or an external image (i.e., a scientific visualization on a computer-generated image). What all spatial transformations have in common is that they involve the use of mental imagery. A more complete description of spatial transformations can be found at `http://iota.gmu.edu/users/trafton/405st.html`.

We will examine the number of times working scientists created or changed an existing external visualization (called physical transformations) and compare that to the number of spatial transformations. This will show us the relative importance of mental imagery in scientific visualization; if scientists spend most of their time creating and manipulating physical images and relatively little time on spatial transformations, this will suggest that scientists do not use much mental imagery while looking at computer-generated scientific visualizations. On the other hand, if there are many more spatial transformations than physical transformations, this will suggest that mental imagery is an important part of scientific visualization. If mental imagery is an important part of scientific visualization (as we expect), then we should find spatial transformations that "connect" the physical display to the mental imagery.

Method

Two datasets were examined. In the first dataset, two astronomers were video-taped as they explored computer generated visual representations of a new set of observational data. The astronomers were instructed not to explain their comments to the researchers, but to carry out their work as though no camera were present. The relevant part of the session lasted about 53 minutes. A more complete description of this dataset can be found in Trickett, Fu, Schunn, and Trafton (2000) and Trickett, Trafton, and Schunn (2000).

In the second dataset, a physicist with a specialty in computational fluid dynamics was examining a subset of results from a computational model that had recently finished running. The scientist had already developed hypotheses and was trying to model another set of data that had been gathered empirically. The scientist was asked to provide a think-aloud protocol as he worked (Ericsson & Simon, 1993). The relevant part of the session lasted about 14 minutes.

All scientists had earned their Ph.Ds over 6 years previously. All utterances were transcribed and segmented, and all off-task segments (e.g., jokes, interruptions, etc.) were discarded for the rest of the data analysis.

Spatial Transformation	**Example**	**Explanation**
Create Mental Image	I mean, in a perfect, in a perfect world, in a perfect sort of spider diagram...	Scientist is creating a mental image of a spider diagram; there is no spider diagram displayed.
Mentally Manipulate: Add	So that [line] would be below the black line	Scientist is adding a new (hypothesizied) line to a current visualization
Comparison: Mental Image to Display	Maybe it's a projection effect, although if that's true, there should be a very large velocity dispersion.	Scientist is comparing a current image to a previously created mental image.

Table 1: Examples of spatial transformations.

The number of times a scientist created a new visualization, the number of times a scientist modified an existing visualization, and the number of spatial transformations were recorded. Table 1 shows several examples of spatial transformations that were used by the scientists.

Results

First, it should be noted that the overall use of spatial transformations in both datasets is remarkably similar. This result is especially surprising because the two datasets were so different in terms of domain, number of scientists, stage of research, etc. Separate coders worked on each dataset, so this similarity in patterns does not appear to be an individual coder effect.

As Figure 1 shows, there are far more spatial transformations than physical transformations, χ^2s for both datasets significant at $p < .001$. Additionally, it is obvious that the most common type of spatial transformations are comparisons, χ^2s for both datasets significant at $p < .001$. These findings suggest that imagery is important in the scientific visualization process. Scientists do not use the computer's visualization capabilities instead of their own mental imagery but instead seem to use both mental imagery and the computer's visualizations. Not only do they use features of the software to tweak the visual image, but they also use spatial transformations to make mental adjustments to that image. Furthermore,

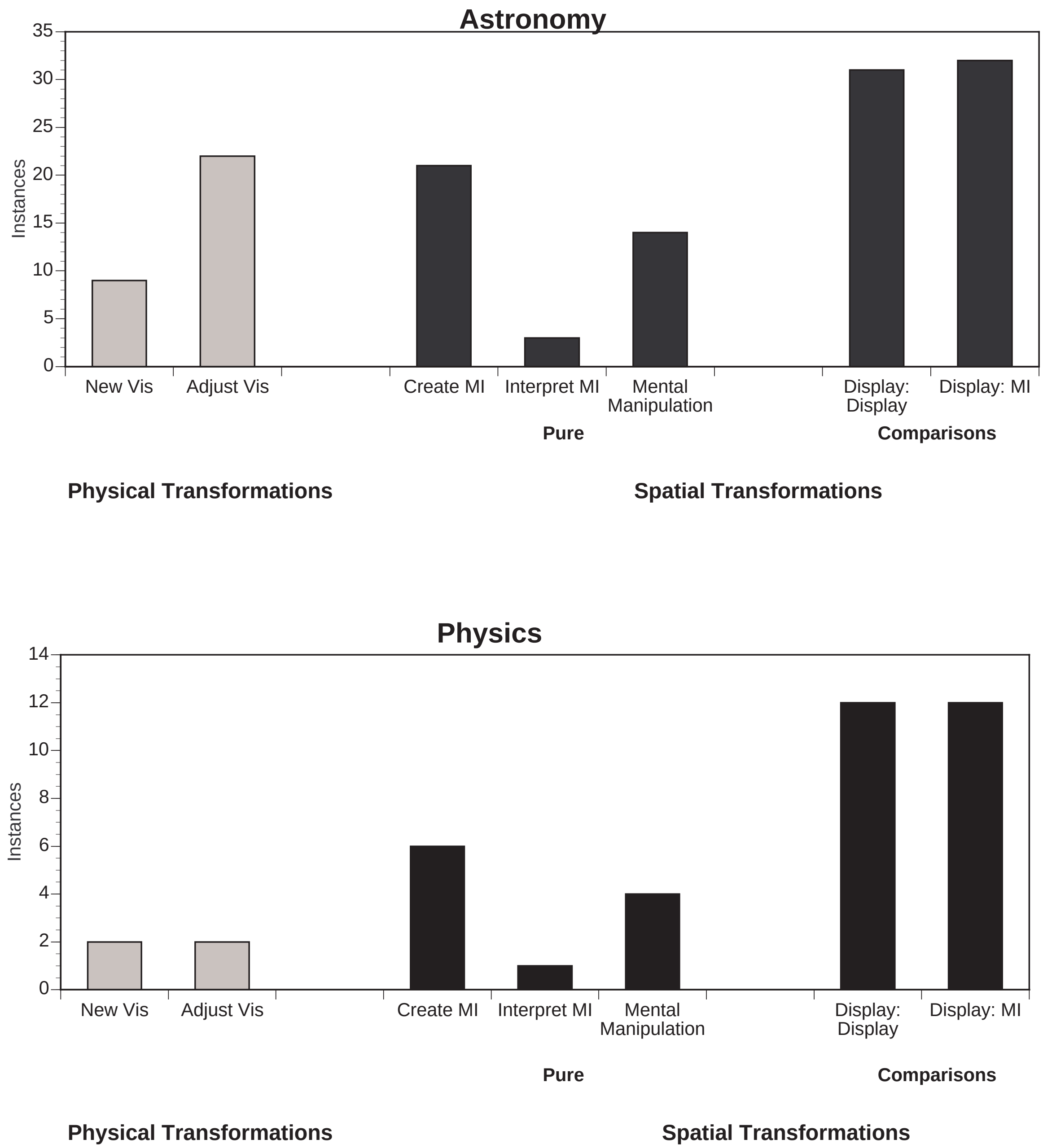

Figure 1. Spatial Transformation Breakdown for both datasets. MI is mental image. The leftmost (gray) bars show the number of physical transformations (new visualizations and the number of times an on-screen visualization was adjusted or modified) and the dark bars show the number of spatial transformations.

they create and interpret mental images that are different from the images in the visual display.

How do scientists connect the mental imagery and the scientific visualizations? The extensive use of comparisons between displays and mental imagery in both datasets suggests that scientists use a comparison process to tie these different visualizations together. In order to explore further the role of comparisons, we coded what the comparisons were used for and related that to the type of comparison made (display to display or mental image to display). This coding was made with the physics dataset alone.

There were three types of comparisons: (a) Determining ID, (b) Aligning, and (c) Comparing surface features. Determining an ID was coded when a comparison was made to get an identification of one of the objects. Aligning was coded when the scientist tried to make an estimation of "fit" between the two images. Comparing surface features was coded when a specific feature of the two images was compared (i.e., colors, size, etc.).

Table 2 shows examples of each type.

Comparison Type	**Number**	**Example**	**Explanation**
Determining ID	2	…except for oh-two who marginally wasn't seeded… which is two-oh's symmetric counterpoint…	Scientist finds oh-two to try to locate where two-oh is
Aligning	13	Well, on the contour plots we saw this spot right here is like a one-three situation	Scientist is remembering a previous contour plot and making an ID on a spot and then making an estimation of how the two spots fit
Comparing Features	9	Uh, the one-three is actually smaller than the oh-three	Scientist is looking at the size of two spots

Table 2: Examples of different types of comparisons and the number of each type that occurred in the physics dataset.

Interestingly, there is a strong relationship between the type of comparison and what items were being compared. When the scientist was comparing 2 images on screen, he was most frequently comparing features (89%), and when he was comparing an image on the screen and a mental image, he was most frequently aligning (85%). As Figure 2 suggests, this relationship is significant, $r_\phi = .726, p < .001$

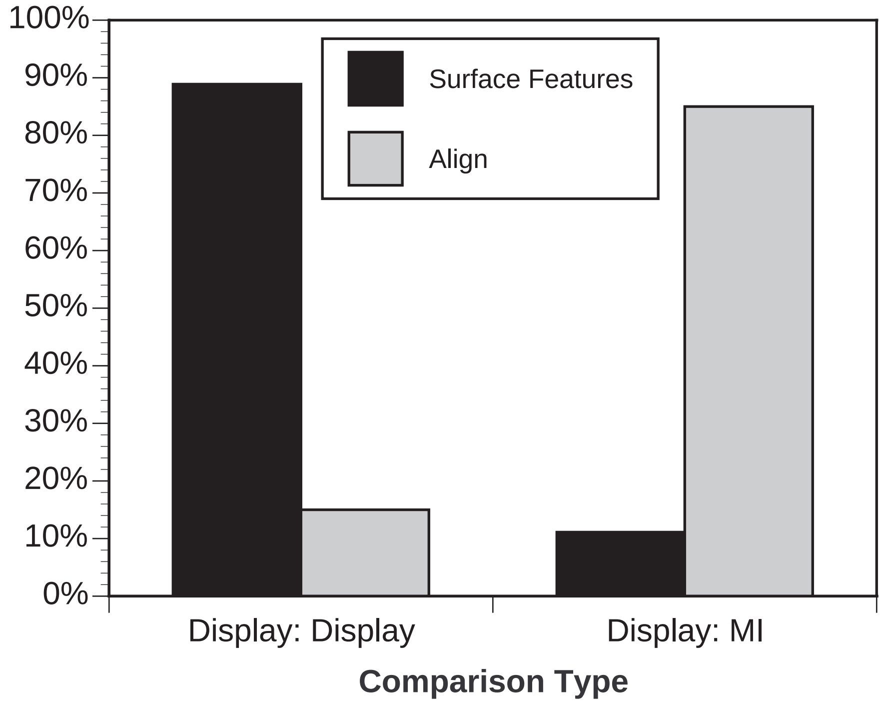

Figure 2. The type of comparison that was made broken down by how that comparison was used (physics dataset). There were only two instances of using a comparison to make an ID, so that category was excluded.

Discussion

This study has shown that, even though today's scientists have very sophisticated scientific visualizations, they still use a great deal of mental imagery. They frequently make mental adjustments to an external image as well as create and interpret a mental image. They keep these mental images connected to the current visualization by means of comparisons between different images. As one might expect, comparisons between two displayed images focus primarily on the similarities and differences between features of those images. However, when the scientists compare displayed images with mental images, they focus on aligning the mental image with the display, in order to estimate the extent to which the mental image "fits" the display image.

The process of aligning, or estimating a fit, may be similar to the process of building a theoretical or computational model and comparing it with empirical data. For example, scientists may mentally create a well understood image from a previous project, and then modify it in various ways to compare it to a current visualization. This process may then help them understand the deep structure and theory behind the creation of the current visualization.

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